2 Technical Overview

This report presents the findings from a study of the life cycle inventories (LCIs) for petroleum diesel and biodiesel. An LCI is a comprehensive quantification of all the energy and environmental flows associated with a product from "cradle to grave." It provides information on:

- Raw materials extracted from the environment
- Energy resources consumed
- Air, water, and solid waste emissions generated.

By "cradle to grave," we mean all the steps from the first extraction of raw materials from the environment to the final end-use of the product. LCIs are invaluable tools for assessing and comparing the overall environmental impacts of various products. One purpose for conducting this study is to assess overall greenhouse gas emissions from these two fuels. Because of the global nature of greenhouse gas effects, these emissions lend themselves very well to life cycle assessment (LCA). We also considered other environmental emissions; particularly regulated air emissions such as carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides and particulate matter. The purpose of this study is to provide LCI data that can be used by industry and government decision-makers considering biodiesel as an alternative fuel. This study is the product of a highly effective partnership between the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE), which has brought together the agricultural and energy expertise needed to adequately address an LCI of biodiesel.

2.1 Stakeholder Involvement

Any good life cycle study makes use of every opportunity to obtain input from all who have a stake in the final outcome. This is especially true for those life cycle studies being conducted to support important government policy decisions. Many of the early decisions made in setting the scope of the study (see section 2.2) can have a profound effect on the outcome of the study. This makes it crucial that all stakeholders have an opportunity to discuss the key assumptions and options for the analysis. But stakeholder involvement cannot stop there. Input throughout the major steps of the project is useful for ensuring the proper use and interpretation of the best available data. Finally, as results from the LCI model become available, offering the opportunity to have stakeholders provide their perspective helps to avoid "tunnel vision." The most important reason for stakeholder involvement in the study is *credibility*. When such studies are done in a vacuum, they stand little chance of getting buy-in from the industries involved. In the end, LCI results are only as good as the "buy-in" or level of credibility they engender.

We made stakeholder involvement a top priority in our study. The following is a list of the groups that provided input to us during the project:

- Petroleum Industry
- Oilseed Processing Industry
- Animal Renderers and Recyclers
- Chemical Process Industry

- Biodiesel Producers
- Engine Manufacturers
- U.S. Department of Agriculture
- U.S. Department of Energy
- U.S. Environmental Protection Agency
- State and Local Governments
- Environmental Public Interest Groups.

Outlined below is a brief description of the process used to continually check in with stakeholders. Throughout this process, we provided opportunities to communicate with us in writing, by phone, and by e-mail, as well as in our face-to-face meetings.

1. Before pen was put to paper, USDA and DOE brought together a consortium of stakeholders at a meeting hosted by USDA in Washington, DC, to discuss the need and goals of our study.
2. Based on input from this group, a preliminary scoping document was put together and distributed for review.
3. A second face-to-face meeting with stakeholders was held to work out the details of the project scope.
4. Once the basic data had been collected on all aspects of the petroleum diesel and biodiesel life cycles, the stakeholders reconvened to review the data. Feedback from this meeting resulted in our updating data sources and filling in gaps in available data.
5. Finally, once results from the LCI model were available, we sought detailed comments from a representative group of stakeholders (that is, those willing to put in the time to study our results). They were given a first draft of this report. Their comments have been carefully compiled. Wherever possible, we have made changes to the model and the report to reflect concerns and criticisms raised by this group. This document is a product of that final review.

The quality of our results is much the better for the input of these groups. We are indebted to the individuals who took the time to participate in this process.

2.2 Scope of the Life Cycle Study

2.2.1 Purpose

The purpose of this study is to conduct an LCI to quantify and compare the comprehensive sets of environmental flows (to and from the environment) associated with both biodiesel and petroleum-based diesel, over their entire life cycles. In addition to the purpose stated, this LCA was initiated to provide the necessary information that could be used to answer the following questions that have been posed by policy makers:

2.2.2 What Is “Biodiesel?”

In its most general sense, “biodiesel” has been used to refer to any diesel fuel substitute that is derived from renewable biomass. In the past few years, biodiesel has taken on a more specific definition and currently refers to a family of products made from vegetable oils or animal fats and alcohol, such as methanol or ethanol. These are called alkyl esters of fatty acids. In order for these alkyl esters of fatty acids to be considered as viable transportation fuels, they must meet stringent quality standards, otherwise they become standard industrial chemicals that are not suitable for diesel applications. Thus, alkyl esters of fatty acids that meet transportation fuel standards are called "biodiesel." One popular process for producing biodiesel is known as "transesterification." This is the technology modeled in this report.

Today, biodiesel is made from a variety of natural oils. Chief among these are soybean oil and rapeseed oil. Rapeseed oil, a close cousin of canola oil, dominates the growing biodiesel industry in Europe. In the United States, biodiesel is being made from soybean oil because more soybean oil is produced than all other sources of fats and oil combined. There are many candidates for feedstocks, including recycled cooking oils, animal fats, and a variety of other oilseed crops. We selected soybean oil as the feedstock used for biodiesel production because of the vast number of data that have been generated about biodiesel from soybean oil.

Today, the most widely used alcohol for biodiesel production is methanol, mostly because of its ease of processing and its relatively low cost. We have chosen to model biodiesel production using methanol. Thus, the working definition of biodiesel in our study is a diesel fuel substitute made via the transesterification of soybean oil with methanol. In industry parlance, this biodiesel product is referred to as soy methyl ester or methyl soyate.

2.2.3 What Is "Petroleum Diesel?"

We defined petroleum diesel as "on-highway" low-sulfur diesel made from crude oil. Recent regulations promulgated by the U.S. Environmental Protection Agency (EPA) as part of its enforcement of the 1990 Clean Air Act Amendments set tougher restrictions on diesel used on the road versus diesel used off the road. The "on highway" diesel must now meet new limits for sulfur content that are an order of magnitude lower than previously allowed (0.05 wt% versus 0.5% sulfur). We restrict our evaluation of petroleum diesel to this new low-sulfur diesel[1].

2.2.4 Defining the Product Application

The choice of the fuels' end-use can greatly affect the life cycle flows. Potential markets for biodiesel cover a wide range of diesel applications, including most truck operations, stationary generation, mining equipment, marine diesel engines, and bus fleets. In this study, we compare the use of petroleum diesel and biodiesel in urban buses. This choice was based on the availability of end-use data. The urban bus market was identified by the nascent U.S. biodiesel industry early on as a near-term opportunity, and a large number of data are available on the performance of diesel bus engines.

2.2.5 What Is Included in the Life Cycle Systems?

Major operations included within the boundary of the petroleum diesel system are:

- Extraction of crude oil from the ground
- Transport of crude oil to an oil refinery
- Refining of crude oil to diesel fuel
- Transport of diesel fuel to its point of use
- Use of the fuel in a diesel bus engine.

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[1] One important clarification should be made about our characterization of petroleum diesel. In our analysis, low-sulfur diesel fuel is used in the product application (urban buses). This is not true for agricultural use of diesel fuel in the production of soybeans. Data for "off highway" diesel-powered tractors were used to characterize performance and emissions of these engines. This off-highway diesel is not held to the same strict standard for sulfur content.

For the biodiesel system, major operations include:

- Produce soybeans
- Transport soybeans to a soy crushing facility
- Recover soybean oil at the crusher
- Transport soybean oil to a biodiesel manufacturing facility
- Conversion of soybean oil to biodiesel
- Transport biodiesel fuel to the point of use
- Use the fuel in a diesel bus engine.
- These operations are not a comprehensive list of what has been modeled in our analysis. These operations include within them detailed processes described elsewhere in this report. For example, extraction of crude oil includes flows from a number of operations such as onshore and offshore drilling and natural gas separation. Onshore drilling is further characterized as either conventional or advanced technology.

We include more than just the energy and environmental flows that occur directly in each of these steps. Energy and environmental inputs from the production of any raw materials used in each step are also included. Generally, life cycle flows are characterized for all raw materials from the point of extracting their primary components from the environment. For example, methanol use in the biodiesel manufacturing facility contributes life cycle flows that go back to the extraction of natural gas used as a feedstock. Likewise, life cycle flows from intermediate energy sources such as electricity are included—back to extraction of coal, oil, natural gas, limestone, and any other primary resources needed.

2.2.6 What Are the Geographical Boundaries?

The LCA is limited to the use of petroleum diesel and biodiesel in the United States. This does not mean that all the steps involved in the life cycles are restricted to domestic boundaries. Petroleum diesel's life cycle, in particular, expands its geographic limits to include foreign crude oil production simply because half the crude oil used in the United States is imported. Other aspects of the geographic limits of the study involve the choice of national versus regional or even site-specific assessment. For domestic operations, we rely on national average data. For foreign operations, we rely on industry average data. Electricity generation is modeled on a national basis. Table 1 and Table 2 present specific information on the geographical scope of the analysis for each stage of the petroleum diesel and biodiesel life cycles.

2.2.7 What Is the Time Frame?

We were faced with two basic options: 1) model technology and markets as they are today; and 2) model a futuristic scenario based on projected technology and markets. We chose to focus on a current time frame. Thus, we consider production and end-use technologies that are available today for both petroleum diesel and biodiesel. This approach ignores future advances in production efficiency and end-use engine technology. By limiting the analysis to the present, it is far more "grounded" and objective because it relies on documented data rather than on potentially optimistic projections. Results from this study provide a baseline for considering future scenarios.

2.2.8 Basis for Comparing the Life Cycles

Common sense suggests that any comparison of two fuel products must be done on the same basis. In the lexicon of LCA, two industrial systems are compared on the same "functional basis." In other words, the fuels are compared based on identical services they provide. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis. For example, a comparison of fuel life cycles for passenger vehicles might characterize all life cycle flows per mile of travel delivered by the vehicle.

The unit used to normalize all life cycle flows is known as the "functional unit." For a more detailed discussion of the definition and protocols established for LCIs, refer to publications from the Society of Environmental Toxicology and Chemistry (SETAC)[2] and EPA[3]. Medium- and heavy-duty diesel engines are typically evaluated on the basis of actual work delivered by the engine. This approach is used because of the variability (or even the irrelevance) of mileage among the various applications for diesel engines. Therefore, we have chosen to compare the life cycle flows of biodiesel and petroleum diesel on the basis of 1 brake horsepower-hour (bhp-h) of work delivered by the bus engine.

Table 1: Geographic Scope of the Petroleum Diesel Life Cycle

Life Cycle Stage	Geographic Scope
Crude Oil Extraction	International average based on the consumption of crude oil in the United States
Crude Oil Transportation	International average transportation distances to the United States
Crude Oil Refining	U.S. national average
Diesel Fuel Transportation	U.S. national average
Diesel Fuel Use	U.S. national average based on urban bus use

Table 2: Geographic Scope of the Biodiesel Life Cycle

Life Cycle Stage	Geographic Scope
Soybean Agriculture	Average based on data from the 14 key soybean-producing states
Soybean Transportation	U.S. national average
Soybean Crushing	U.S. national average based on modeling of a generic U.S. crushing facility
Soybean Oil Transport	U.S. national average
Soybean Oil Conversion	U.S. average based on modeling of a generic biodiesel facility
Biodiesel Transportation	U.S. national average
Biodiesel Fuel Use	U.S. national average based on urban bus use

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[2] SETAC, *A Technical Framework for Life-Cycle Assessments,* Society of Environmental Toxicology and Chemistry, Washington DC, 1991; SETAC, *Guidelines for Life-Cycle Assessment: A "Code of Practice,"* Society of Environmental Toxicology and Chemistry, Washington, DC, 1993; SETAC, *A Conceptual Framework for Life-Cycle Impact Assessment,* Society of Environmental Toxicology and Chemistry, Washington, DC, 1993; SETAC, *Life Cycle Assessment Data Quality: A Conceptual Framework*, Society of Environmental Toxicology and Chemistry, Washington ,DC, 1994.

[3] EPA: *Life Cycle Design Manual: Environmental Requirements and the Product System,* EPA/600/R-92/226, 1993; U.S. Environmental Protection Agency, *Life-Cycle Assessment: Inventory Guidelines and Principles*, EPA/600-R-92-245, 1993; U.S. Environmental Protection Agency, *Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis,* EPA/530-R-95-010, 1995.

2.3 Key Assumptions

The details of the assumptions and modeling steps of the life cycle are presented in subsequent sections of this report, although two general assumptions applied in the modeling should be highlighted. First, national average distances were used for transport of all feedstocks, intermediates, and products. The effect of this assumption was tested in a sensitivity analysis. Second, both fuels are assumed to be used in "current" diesel engines, defined as engines calibrated to meet 1994 EPA regulations for diesel exhaust when operated on low-sulfur petroleum diesel. Other assumptions worth noting include:

- Crude oil delivery from domestic and foreign sources are split almost evenly
- Best available refinery data for extant facilities were used to model a "generic" refinery
- Emissions from petroleum diesel are assumed to meet 1994 engine emissions standards.
- Biodiesel assumptions worth noting include:
- Agriculture practices and yields are based on weighted averages for 14 soybean-producing states
- Emissions are based on actual engine data for biodiesel emissions that are then modeled as changes in the oxygen content[4] in the fuel
- Energy efficiencies of biodiesel-fueled engines are identical to those of petroleum diesel-fueled engines[5]
- Biomass-derived carbon dioxide (CO_2) in the fuel emissions is recycled in soybean production.

For details on the bases for these assumptions, refer to the sections describing each stage of the life cycles.

2.4 Findings

LCI results are presented for 100% biodiesel (known as "B100"), a 20% blend of biodiesel with petroleum diesel (known as "B20"), and petroleum diesel. These results include estimates of:

- Overall energy requirements
- CO_2 emissions
- Other regulated and non-regulated air emissions. Regulated pollutants include carbon monoxide (CO), particulate matter less than 10 microns in size (PM10), non-methane hydrocarbons (NMHC), and nitrogen oxides (NO_x). Non-regulated air emissions include methane (CH_4), formaldehyde, benzene, total hydrocarbons (THC), and total particulate matter (TPM).
- Water emissions
- Solid wastes.

These life cycle flows are presented for the base-case scenarios and for two sensitivity studies. The base case describes petroleum diesel and biodiesel life cycle flows for "national average" scenarios.

The purpose of conducting sensitivity studies on the life cycle of biodiesel was to establish the potential range for improvement in the fuel, as well as to establish the range of possible error associated with the

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[4] Diesel fuel contains no oxygen. The amount of oxygen is a measure of biodiesel content in the fuel. In addition, percent oxygen proves to be a good basis for predicting emissions.

[5] This is substantiated with an analysis of engine performance data.

assumptions made in the model. The LCI assumes a "current" time frame—that is, we are looking at options for improvement of agriculture, soybean oil recovery, conversion technology, and engine technology within a short-term horizon. This sets realistic limitations on the assumptions used in the model.

In each life cycle step we considered the potential for near-term improvement. Two main areas were identified. First, we felt it was important to understand the impact of location on biodiesel production. This allows us to consider the benefits of the best agricultural productivity available in the United States and the shortest distances for transport of fuel and materials. This sets an upper bound on biodiesel benefits from the perspective of current agricultural practices and transportation logistics.

Second, we identified the conversion of soybean oil to biodiesel as an aspect of the life cycle that has significant impact on energy use and emissions and that has a broad range of efficiencies, depending on the commercial technology used. Our base case estimate of the energy requirements for soy oil conversion is based on a preliminary engineering design prepared for this study. The design was loosely based on data from an extant transesterification plant in Kansas City, Missouri. Our energy budget proved to be much lower than that reported for the facility in Kansas City. A review of the literature on recent transesterification technology revealed that our design estimate is at the high end of the range of recently published literature values. To deal with this disparity in energy estimates for conversion of soy oil to biodiesel, we decided to look at the range of reported energy budgets as a sensitivity study.

Changes in engine technology may also be an avenue for improving biodiesel on a life cycle basis. We opted to forego this area in our sensitivity analysis because of limited data. Thus, we present in this report the results of two sensitivity studies:

- The base case for B100 is compared with the LCI for an optimal biodiesel location (Chicago). The choice of an optimal location is based on an evaluation of regions with the most efficient production of soybeans, local concentration of soybean producers, and large end-use markets for urban buses.
- Results for a range of high and low energy demands for soybean conversion to biodiesel are compared to determine the impact of this stage of the biodiesel life cycle on overall emissions and energy flows. Low and high values for energy consumption were based on a survey of technical literature on the most recent technologies commercially available.

2.4.1 Results of the Base Case Study

The results provided here allow the reader to make a nominal comparison of biodiesel and petroleum diesel. By nominal, we mean that the LCIs calculated for each fuel reflect generic "national average" models. The only exception to this statement is soybean agriculture data, which are provided on a state-by-state basis for the 14 key soybean-producing states. Implicit in such a nominal comparison is that there are no regional differences that could affect any of the stages of each fuel's life cycle. There will, of course, be differences that will affect each fuel.

In most cases, biodiesel is interchangeable with petroleum diesel without any need to modify today's diesel engine. However, one key issue for biodiesel use that should be explicitly is the effect of regional climate on the performance of the fuel. This fuel's cold flow properties may limit its use in certain parts of the country during the winter. This caveat should be kept in mind. Means of mitigating biodiesel's cold flow properties are being evaluated by researchers, though no clear solution is at hand. Low-sulfur #2 diesel fuel has similar limitations that are currently addressed with the use of additives and by blending this fuel with #1 diesel fuel.

2.4.1.1 Life Cycle Energy Balance

LCIs provide an opportunity to quantify the total energy demands and the overall energy efficiencies of processes and products. Understanding the overall energy requirements of biodiesel is key to our understanding the extent to which biodiesel made from soybean oil is a "renewable energy" source. Put quite simply, the more fossil energy required to make a fuel, the less we can say that this fuel is "renewable". Thus, the renewable nature of a fuel can vary across the spectrum of "completely renewable." (i.e., no fossil energy input) to nonrenewable (i.e., fossil energy inputs as much or more than the energy output of the fuel)[6]. Energy efficiency estimates help us to determine how much additional energy must be expended to convert the energy available in raw materials used in the fuel's life cycle to a useful transportation fuel. The following sections describe these basic concepts in more detail, as well as the results of our analysis of the life cycle energy balances for biodiesel and petroleum diesel.

2.4.1.1.1 Types of Life Cycle Energy Inputs

In this study, we track several types of energy flows through each fuel life cycle. For clarity, each of these energy flows is defined below.

- *Total Primary Energy*. All raw materials extracted from the environment can contain[7] energy. In estimating the total primary energy inputs to each fuel's life cycle, we consider the cumulative energy content of all resources extracted from the environment.
- *Feedstock Energy*. Energy contained in raw materials that end up directly in the final fuel product is termed "feedstock energy." For biodiesel production, feedstock energy includes the energy contained in the soybean oil and methanol feedstocks that are converted to biodiesel. Likewise, the petroleum directly converted to diesel in a refinery contains primary energy that is considered a feedstock energy input for petroleum diesel. Feedstock energy is a subset of the primary energy inputs.
- *Process Energy*. The second major subset of primary energy is "process energy." This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the fuel product itself, but is needed in the processing of feedstock energy into its final fuel product form. Process energy consists primarily of coal, natural gas, uranium, and hydroelectric power sources consumed directly or indirectly in the fuel's life cycle.
- *Fossil Energy*. Because we are concerned about the renewable nature of biodiesel, we also track the primary energy that comes from fossil sources specifically (coal, oil, and natural gas). All three of the previously defined energy flows can be categorized as fossil or nonfossil energy.
- *Fuel Product Energy*. The energy contained in the final fuel product, which is available to do work in an engine, is what we refer to as the "fuel product energy". All other things being equal, fuel product energy is a function of the energy density of each fuel.

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[6] This last statement is an oversimplification. We consider the energy trapped in soybean oil to be renewable because it is solar energy stored in liquid form through biological processes that are much more rapid than the geologic time frame associated with fossil energy formation. Also, other forms of nonrenewable energy besides fossil fuel exist.

[7] The energy "contained" in a raw material is the amount of energy that would be released by the complete combustion of that raw material. This "heat of combustion" can be measured in two ways: as a higher heating value or a lower heating value. Combustion results in the formation of CO_2 and water. Higher heating values consider the amount of energy released when the final combustion products are gaseous CO_2 and liquid water. Lower heating values take into account the loss of energy associated with the vaporization of the liquid water combustion product. Our energy content is based on the lower heating values for each material.

2.4.1.1.2 Defining Energy Efficiency

We report two types of energy efficiency. The first is the overall "life cycle energy efficiency". The second is what we refer to as the "fossil energy ratio". Each elucidates a different aspect of the life cycle energy balance for the fuels studied.

The calculation of the life cycle energy efficiency is simply the ratio of fuel product energy to total primary energy:

Life Cycle Energy Efficiency = Fuel Product Energy/Total Primary Energy

It is a measure of the amount of energy that goes into a fuel cycle, which actually ends up in the fuel product. This efficiency accounts for losses of feedstock energy and additional process energy needed to make the fuel.

The fossil energy ratio tells us something about the degree to which a given fuel is or is not renewable. It is defined simply as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel:

Fossil Energy Ratio = Fuel Energy/Fossil Energy Inputs

If the fossil energy ratio has a value of zero, then a fuel is not only completely nonrenewable, but it provides no useable fuel product energy as a result of the fossil energy consumed to make the fuel. If the fossil energy ratio is equal to 1, then this fuel is still nonrenewable. A fossil energy ratio of one means that no loss of energy occurs in the process of converting the fossil energy to a useable fuel. For fossil energy ratios greater than 1, the fuel actually begins to provide a leveraging of the fossil energy required to make the fuel available for transportation. As a fuel approaches being "completely" renewable, its fossil energy ratio approaches "infinity." In other words, a completely renewable fuel has no requirements for fossil energy.

From a policy perspective, these are important considerations. Policymakers want to understand the extent to which a fuel increases the renewability of our energy supply. Another implication of the fossil energy ratio is the question of climate change. Higher fossil energy ratios imply lower net CO_2 emissions. This is a secondary aspect of the ratio, as we are explicitly estimating total CO_2 emissions from each fuel's life cycle. Nevertheless, the fossil energy ratio serves as a check on our calculation of CO_2 life cycle flows (since the two should be correlated).

2.4.1.1.3 Petroleum Diesel Life Cycle Energy Consumption

Table 3 and Figure 1 show the total primary energy requirements for the key steps in the production and use of petroleum diesel. The LCI model shows that 1.2007 MJ of primary energy is used to make 1 MJ of petroleum diesel fuel. This corresponds to a life cycle energy efficiency of 83.28%[8].

The distribution of the primary energy requirements for each stage of the petroleum diesel life cycle is shown in Table 3. In Figure 1, the stages of petroleum diesel production are ranked from highest to lowest in terms of primary energy demand. Ninety-three percent of the primary energy demand is for extracting crude oil from the ground. About 88% of the energy shown for crude oil extraction is associated with the energy value of the crude oil itself. The crude oil refinery step for making diesel fuel dominates the remaining 7% of the primary energy use.

Removing the feedstock energy of the crude itself from the primary energy total allows us to analyze the relative contributions of the process energy used in each life cycle. Process energy used in each stage of the petroleum life cycle is shown in Figure 2. Process energy demand represents 20% of the energy

[8] Using the total primary energy reported in Table 3, Life Cycle Energy Efficiency = 1 MJ of Fuel Product Energy/1.2007 MJ of Primary Energy Input = 0.8328.

ultimately available in the petroleum diesel fuel product. About 90% of the total process energy is in refining (60%) and extraction (29%). The next largest contribution to total process energy is for transporting foreign crude oil to domestic petroleum refiners.

Table 3: Primary Energy Requirements for the Petroleum Diesel Life Cycle

Stage	Primary Energy (MJ per MJ of Fuel)	Percent
Domestic Crude Production	0.5731	47.73%
Foreign Crude Oil Production	0.5400	44.97%
Domestic Crude Transport	0.0033	0.28%
Foreign Crude Transport	0.0131	1.09%
Crude Oil Refining	0.0650	5.41%
Diesel Fuel Transport	0.0063	0.52%
Total	1.2007	100.00%

There are some significant implications in the process energy results shown in Figure 2 regarding trends for foreign and domestic crude oil production and use. Transportation of foreign crude oil carries with it a fourfold penalty for energy consumption compared to domestic petroleum transport because the overseas transport of foreign oil by tanker increases the travel distance for foreign oil by roughly a factor of four.

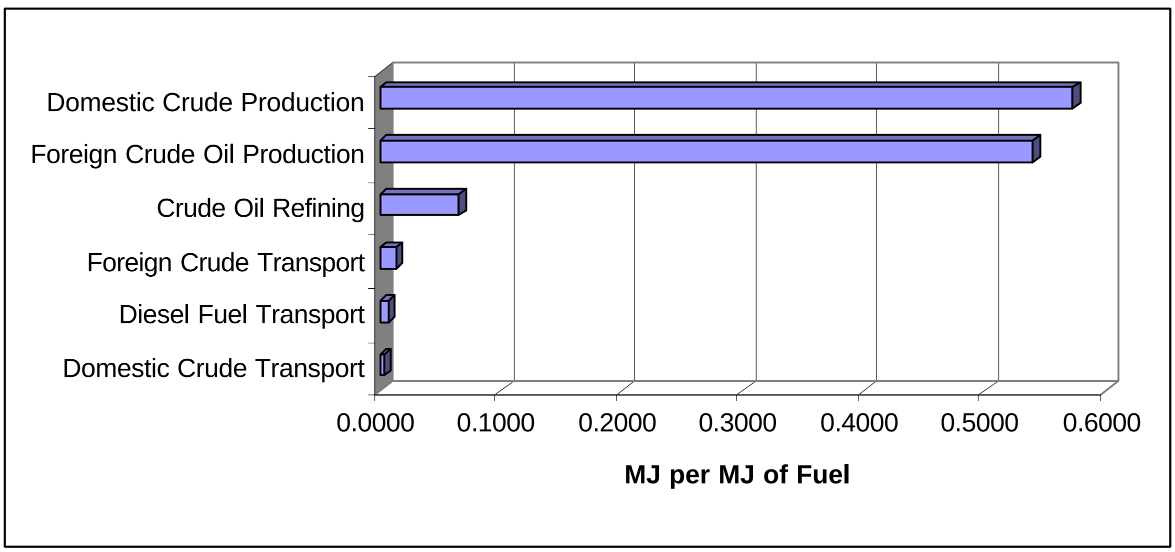

Figure 1: Ranking of Primary Energy Demand for the Stages of Petroleum Diesel Production

At the same time, domestic crude oil extraction is more energy intensive than foreign crude oil production. Advanced oil recovery practices in the United States represent 11% of the total production volume, compared to 3% for foreign oil extraction. Advanced oil recovery uses twice as much primary energy per kilogram of oil compared to conventional extraction. Per kilogram of oil out of the ground, advanced crude oil extraction requires almost 20 times more process energy than onshore domestic crude oil extraction because the processes employed are energy intensive and the amount of oil recovered is low compared to other practices. Domestic crude oil supply is essentially equal to foreign oil supply (50.26% versus 49.74%, respectively) in our model, but its process energy requirement is 62% higher than that of foreign crude oil production (see Figure 2).

If our present trend of increased dependence on foreign oil continues, we can expect the life cycle energy efficiency of petroleum diesel to worsen because of the higher energy costs of transporting foreign crude to the United States. In addition, with declining domestic oil supplies, we may well see increased energy penalties for domestic crude oil extraction, as the practice of advanced oil recovery increases.

Table 4 and Figure 3 summarize the fossil energy inputs with respect to petroleum diesel's energy output. Petroleum diesel uses 1.1995 MJ of fossil energy to produce 1 MJ of fuel product energy. This corresponds to a fossil energy ratio of 0.8337[9]. Because the main feedstock for diesel production is itself a fossil fuel, it is not surprising that this ratio is almost identical to the life cycle energy efficiency of 83.28%. In fact, fossil energy associated with the crude oil feedstock accounts for 93% of the total fossil energy consumed in the life cycle. The fossil energy ratio is slightly less than the life cycle energy ratio because there is a very small contribution to the total primary energy demand, which is met through hydroelectric and nuclear power supplies related to electricity generation.

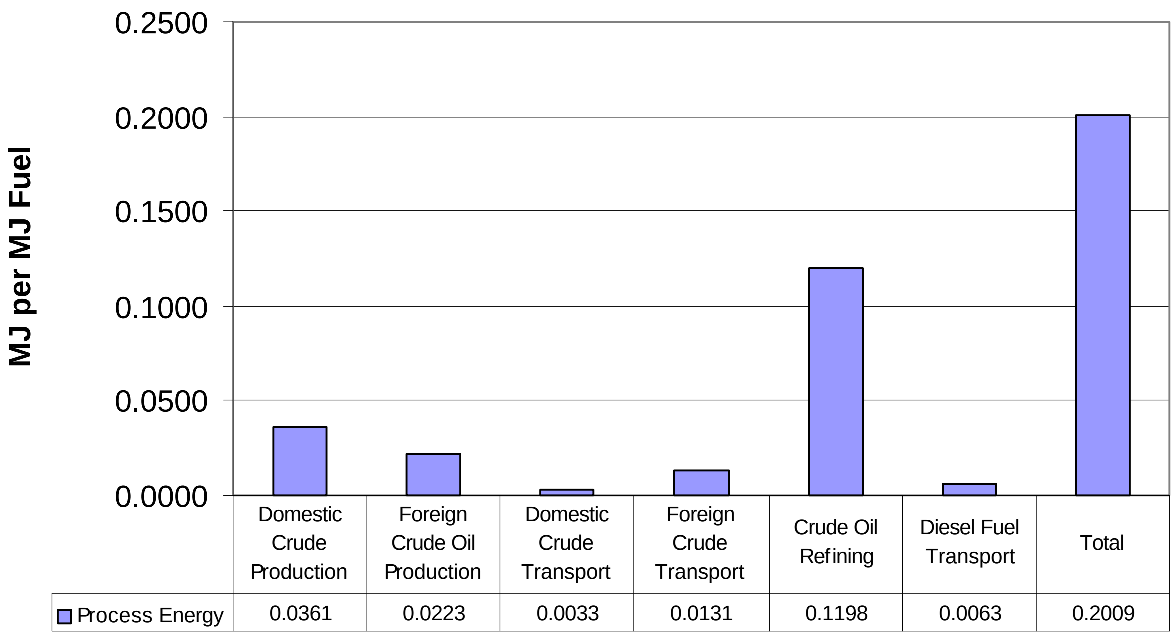

Figure 2: Process Energy Demand for Petroleum Diesel Life Cycle

2.4.1.1.4 Biodiesel Life Cycle Energy Demand

Table 5 and Figure 4 present the total primary energy demand used in each stage of the biodiesel life cycle. One MJ of biodiesel requires an input of 1.2414 MJ of primary energy, resulting in a life cycle energy efficiency of 80.55%. Biodiesel is comparable to petroleum diesel in the conversion of primary energy to fuel product energy (80.55% versus 83.28%). The largest contribution to primary energy (87%) is the soybean oil conversion step because this is where we have chosen to include the feedstock energy

[9] Fossil Energy Ratio = 1 MJ Fuel Energy/1.1995 MJ of Fossil Energy Input = 0.8337.

associated with the soybean oil itself[10]. As with the petroleum life cycle, the stages of the life cycle that are burdened with the feedstock energy overwhelm all other stages. Had the soybean oil energy been included with the farming operation, then soybean agriculture would have been the dominant consumer of primary energy. This is analogous to placing the crude oil feedstock energy in the extraction stage for petroleum diesel fuel. The next two largest primary energy demands are for soybean crushing and soybean oil conversion. They account for most of the remaining 13% of the total demand.

Table 4: Fossil Energy Requirements for the Petroleum Diesel Life Cycle

Stage	Fossil Energy (MJ per MJ of Fuel)	Percent
Domestic Crude Production	0.572809	47.75%
Foreign Crude Oil Production	0.539784	45.00%
Domestic Crude Transport	0.003235	0.27%
Foreign Crude Transport	0.013021	1.09%
Crude Oil Refining	0.064499	5.38%
Diesel Fuel Transport	0.006174	0.51%
Total	1.199522	100.00%

When we look at process energy separately from primary energy, we see that energy demands in the biodiesel life cycle are not dominated by soybean oil conversion (Figure 5). The soybean crushing and soy oil conversion to biodiesel demand the most process energy (34.25 and 34.55%, respectively, of the total demand). Agriculture accounts for most of the remaining process energy consumed in life cycle for biodiesel (almost 25% of total demand). Each transportation step is only 2%-3% of the process energy used in the life cycle.

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[10] Energy contained in the soybean oil itself represents, in effect, the one place in the biodiesel life cycle where input of solar energy is accounted for. Total radiant energy available to soybean crops is essentially viewed as "free" in the life cycle calculations. It becomes an accountable element of the life cycle only after it has been incorporated in the soybean oil itself. This is analogous to counting the feedstock energy of crude petroleum as the point in its life cycle where solar energy input occurs. Petroleum is essentially stored solar energy. The difference between petroleum and soybean oil as sinks for solar energy is their time scale. While soybean oil traps solar energy on a rapid ("real time") basis, petroleum storage represents a process that occurs on a geologic time scale. This difference in the dynamic nature of solar energy utilization is the key to our definitions of renewable and nonrenewable energy.

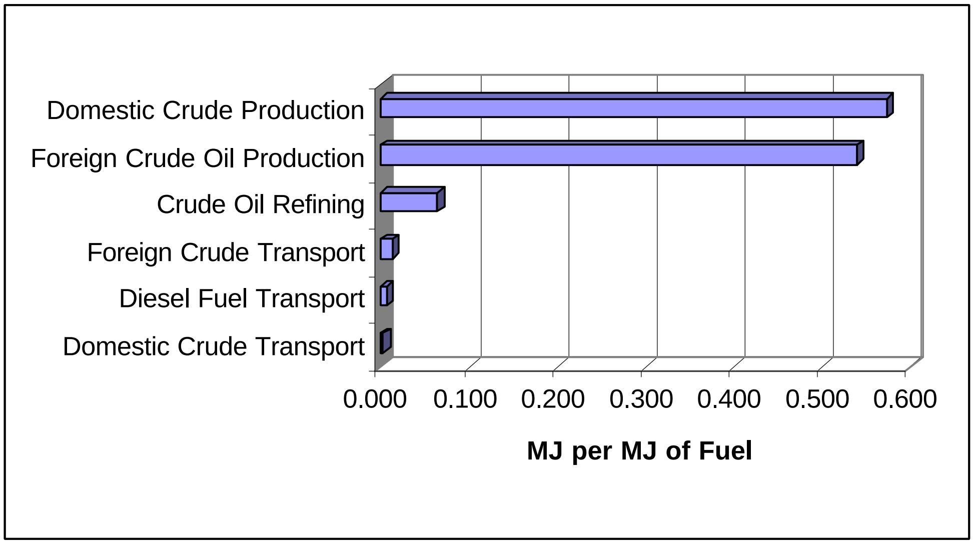


Figure 3: Ranking of Fossil Energy Demand for Stages of the Petroleum Diesel Life Cycle

Table 5: Primary Energy Requirements for Biodiesel Life Cycle

Stage	Primary Energy (MJ per MJ of Fuel)	Percent
Soybean Agriculture	0.0660	5.32%
Soybean Transport	0.0034	0.27%
Soybean Crushing	0.0803	6.47%
Soy Oil Transport	0.0072	0.58%
Soy Oil Conversion	1.0801	87.01%
Biodiesel Transport	0.0044	0.35%
Total	1.2414	100.00%

Table 6 and Figure 6 summarize the fossil energy requirements for the biodiesel life cycle. Because 90% of its feedstock requirements are renewable (that is, soybean oil), biodiesel's fossil energy ratio is favorable. Biodiesel uses 0.3110 MJ of fossil energy to produce one MJ of fuel product; this equates to a fossil energy ratio of 3.215. In other words, the biodiesel life cycle produces more than three times as much energy in its final fuel product as it uses in fossil energy. Fossil energy demand for the conversion step is almost twice that of its process energy demand, making this stage of the life cycle the largest contributor to fossil energy demand. The use of methanol as a feedstock in the production of biodiesel accounts for this high fossil energy demand. We have counted the feedstock energy of methanol coming into the life cycle at this point, assuming that the methanol is produced from natural gas. This points out an opportunity for further improvement of the fossil energy ratio by substituting natural gas-derived methanol with renewable sources of methanol, ethanol or other alcohols.

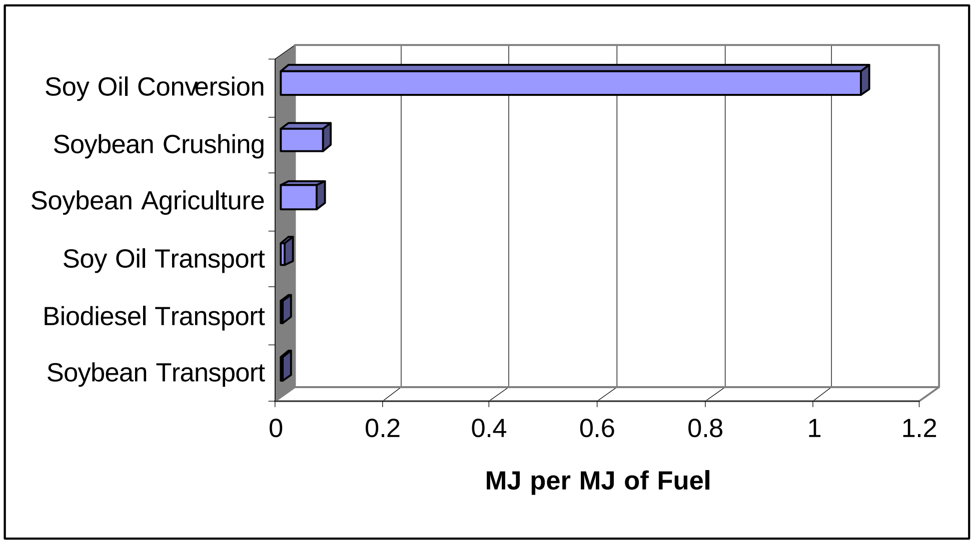
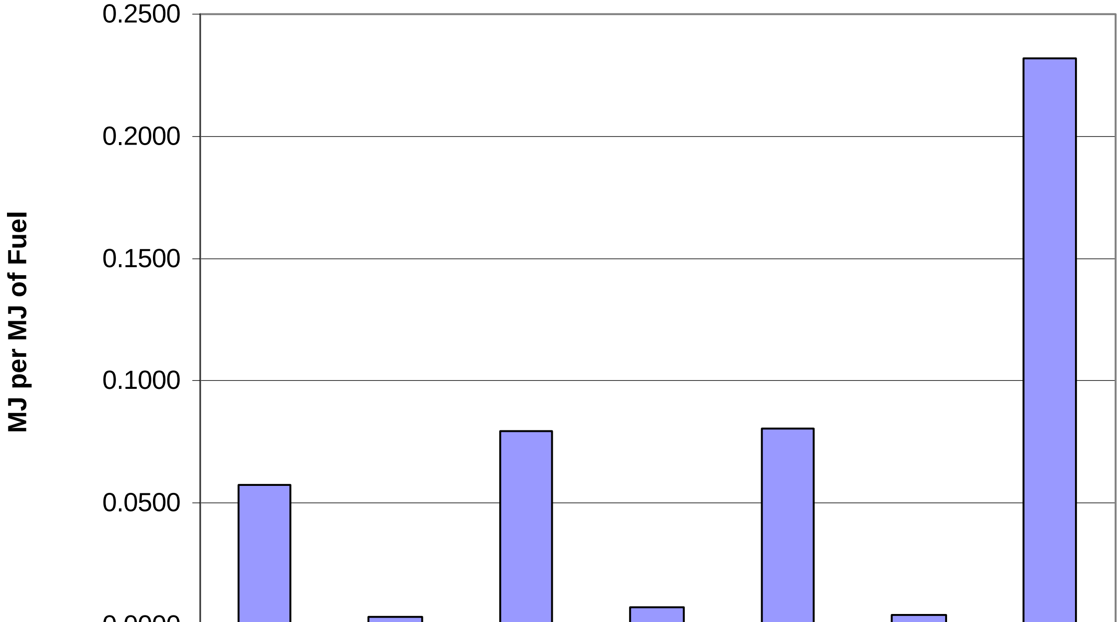


Figure 4: Ranking of Primary Energy Demand for Stages of the Biodiesel Life Cycle



	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soy Oil Transport	Soy Oil Conversion	Biodiesel Transport	Total
Process Energy	0.0573	0.0034	0.0794	0.0072	0.0801	0.0044	0.2318

Figure 5: Process Energy Requirements for Biodiesel Life Cycle

Table 6: Fossil Energy Requirements for the Biodiesel Life Cycle

Stage	Fossil Energy (MJ per MJ of Fuel)	Percent
Soybean Agriculture	0.0656	21.08%
Soybean Transport	0.0034	1.09%
Soybean Crushing	0.0796	25.61%
Soy Oil Transport	0.0072	2.31%
Soy Oil Conversion	0.1508	48.49%
Biodiesel Transport	0.0044	1.41%
Total	0.3110	100.00%

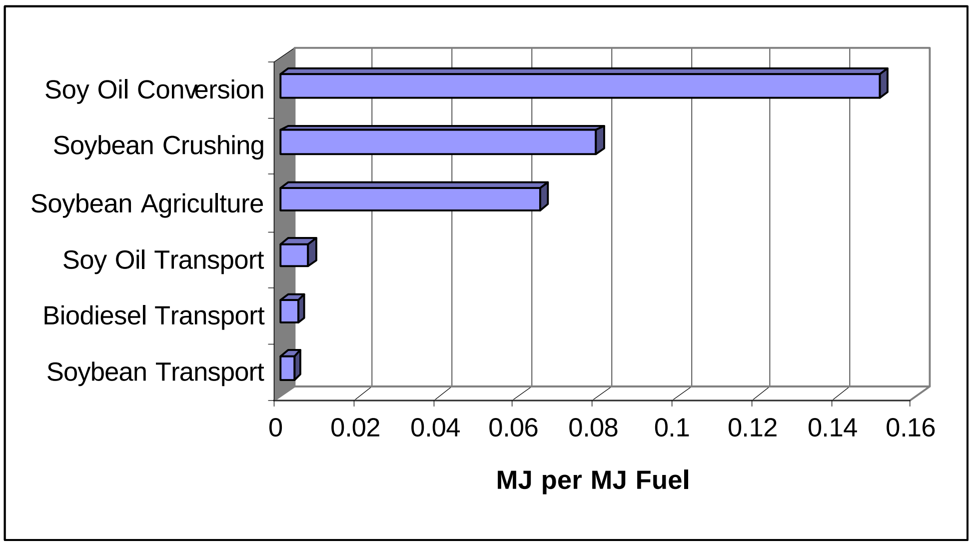


Figure 6: Fossil Energy Requirements versus Fuel Product Energy for the Biodiesel Life Cycle

2.4.1.1.5 Effect of Biodiesel on Life Cycle Energy Demands

Compared on the basis of primary energy inputs, biodiesel and petroleum diesel are essentially equivalent. Biodiesel has a life cycle energy efficiency of 80.55%, compared to 83.28% for petroleum diesel. The slightly lower efficiency reflects a slightly higher demand for process energy across the life of cycle for biodiesel. On the basis of fossil energy inputs, biodiesel enhances the effective use of this finite energy resource. Biodiesel leverages fossil energy inputs by more than three to one.

2.4.1.2 CO_2 Emissions

2.4.1.2.1 Accounting for Biomass-Derived Carbon

Biomass plays a unique role in the dynamics of carbon flow in our biosphere. Biological cycling of carbon occurs when plants (biomass such as soybean crops) convert atmospheric CO_2 to carbon-based compounds through photosynthesis. This carbon is eventually returned to the atmosphere as organisms consume the biological carbon compounds and respire. Biomass derived fuels reduce the net atmospheric carbon in two ways. First, they participate in the relatively rapid biological cycling of carbon to the atmosphere (via engine tailpipe emissions) and from the atmosphere (via photosynthesis). Second, these fuels displace the use of fossil fuels. Combustion of fossil fuels releases carbon that took millions of years to be removed from the atmosphere, while combustion of biomass fuels participates in a process that allows rapid recycle of CO_2 to fuel. The net effect of shifting from fossil fuels to biomass-derived fuels is, thus, to reduce the amount of CO_2 present in the atmosphere.

Because of the differences in the dynamics of fossil carbon flow and biomass carbon flow to and from the atmosphere, biomass carbon must be accounted for separately from fossil-derived carbon. The LCI model tracks carbon from the point at which it is taken up as biomass via photosynthesis to its final combustion as biodiesel used in an urban bus. The biomass-derived carbon that ends up as CO_2 leaving the tailpipe of the bus is subtracted from the total CO_2 emitted by the bus because it is ultimately reused in the production of new soybean oil. In order to ensure that we accurately credit the biodiesel LCI for the amount of recycled CO_2, we provide a material balance on biomass carbon.

The material balance shows all the biomass carbon flows associated with the delivery of 1 bhp-h of engine work (Figure 7). For illustration purposes, only the case of 100% biodiesel is shown. Lower blend rates proportionately lower the amount of biomass carbon credited as part of the recycled CO_2. Carbon incorporated in the meal fraction of the soybeans is not included in the carbon balance. Only carbon in the fatty acids and triglycerides that are used in biodiesel production are tracked. Not all the carbon incorporated in fatty acids and triglycerides ends up as CO_2 after combustion of biodiesel. Some oil loss occurs in the meal by-product. Glycerol is removed from the triglycerides as a by-product. Fatty acids are removed as soaps and waste. Finally, carbon released in combustion ends up in the form of CO_2, CO, THC, and TPM. Of the 169.34 grams of carbon absorbed in the soybean agriculture stage, only 148.39 grams (87%) end up in biodiesel. After accounting for carbon that ends up in other combustion products, 148.05 grams of carbon end up as 543.34 grams of tailpipe CO_2. This CO_2 is subtracted from the diesel engine emissions as part of the biological recycle of carbon. No credit is taken for the 13% of the carbon that ends up in various by-products and waste streams.

2.4.1.2.2 Comparison of CO_2 Emissions for Biodiesel and Petroleum Diesel

Table 7 summarizes CO_2 flows from the total life cycles of biodiesel and petroleum diesel and the total CO_2 released at the tailpipe for each fuel. The dominant sources of CO_2 for both the petroleum diesel life cycle and the biodiesel life cycle is the combustion of fuel in the bus. For petroleum diesel, CO_2 emitted from the tailpipe of the bus represents 86.54% of the total CO_2 emitted across the entire life cycle of the fuel. Most remaining CO_2 comes from emissions at the oil refinery, which contributes 9.6% of the total CO_2 emissions. For biodiesel, 84.43% of the CO_2 emissions occur at the tailpipe. The remaining CO_2 comes almost equally from soybean agriculture, soybean crushing, and conversion of soy oil to biodiesel.

At the tailpipe, biodiesel emits 4.7% more CO_2 than petroleum diesel, most of which is renewable. The nonrenewable portion comes from the methanol. Biodiesel generates 573.96 g/bhp-h compared with 548.02 g/bhp-h for petroleum diesel. The higher CO_2 levels result from more complete combustion and the concomitant reductions in other carbon-containing tailpipe emissions. As Figure 8 shows, the overall life cycle emissions of CO_2 from B100 are 78.45% lower than those of petroleum diesel. The reduction is a direct result of carbon recycling in soybean plants. B20, the most commonly used form of biodiesel in the US, reduces net CO_2 emissions by 15.66% per gallon of fuel used.

Table 7: Tailpipe Contribution to Total Life Cycle CO_2 for Petroleum Diesel and Biodiesel (g CO_2/bhp-h)

Fuel	Total Life Cycle Fossil CO_2	Total Life Cycle Biomass CO_2	Total Life Cycle CO_2	Tailpipe Fossil CO_2	Tailpipe Biomass CO_2	Total Tailpipe CO_2	% of Total CO_2 from Tailpipe
Petroleum Diesel	633.28	0.00	633.28	548.02	0.00	548.02	86.54%
B100	136.45	543.34	679.78	30.62	543.34	573.96	84.43%

2.4.1.3 Primary Resource Consumption for Biodiesel and Petroleum Diesel

The use of B100 as a substitute for petroleum diesel effects a 95% reduction in life cycle consumption of petroleum. Figure 9 compares petroleum oil consumption for petroleum diesel, B20, and B100. The 20% blend of biodiesel provides a proportionate reduction of 19%.

Consumption of coal and natural gas is a different story (Figure 10). The use of B100 increases life cycle consumption of coal by 19%. This reflects the higher overall demand for electricity in the biodiesel life cycle, relative to petroleum diesel. Electricity demand for soybean crushing is the dominant factor in electricity consumption for biodiesel because of the mechanical processing and solids handling equipment involved in this step. Life cycle consumption of natural gas increases by 77% for biodiesel versus petroleum diesel. Two factors contribute to this increase: 1) the assumed use of natural gas for the supply of steam and process heat in soybean crushing and soy oil conversion, and 2) the use of natural gas to produce methanol used in the conversion step.

The biodiesel life cycle imposes a higher burden on water resources than the petroleum diesel life cycle. Water use for petroleum diesel is not even visible on a plot scaled to show biodiesel use (Figure 11). That is because the biodiesel life cycle uses water at a rate that is three orders of magnitude higher than that of petroleum diesel. The impact of this water use is not addressed in this report. We offer no simple way to compare water use between the two life cycles because there is no simple equivalency in its use and final disposition.

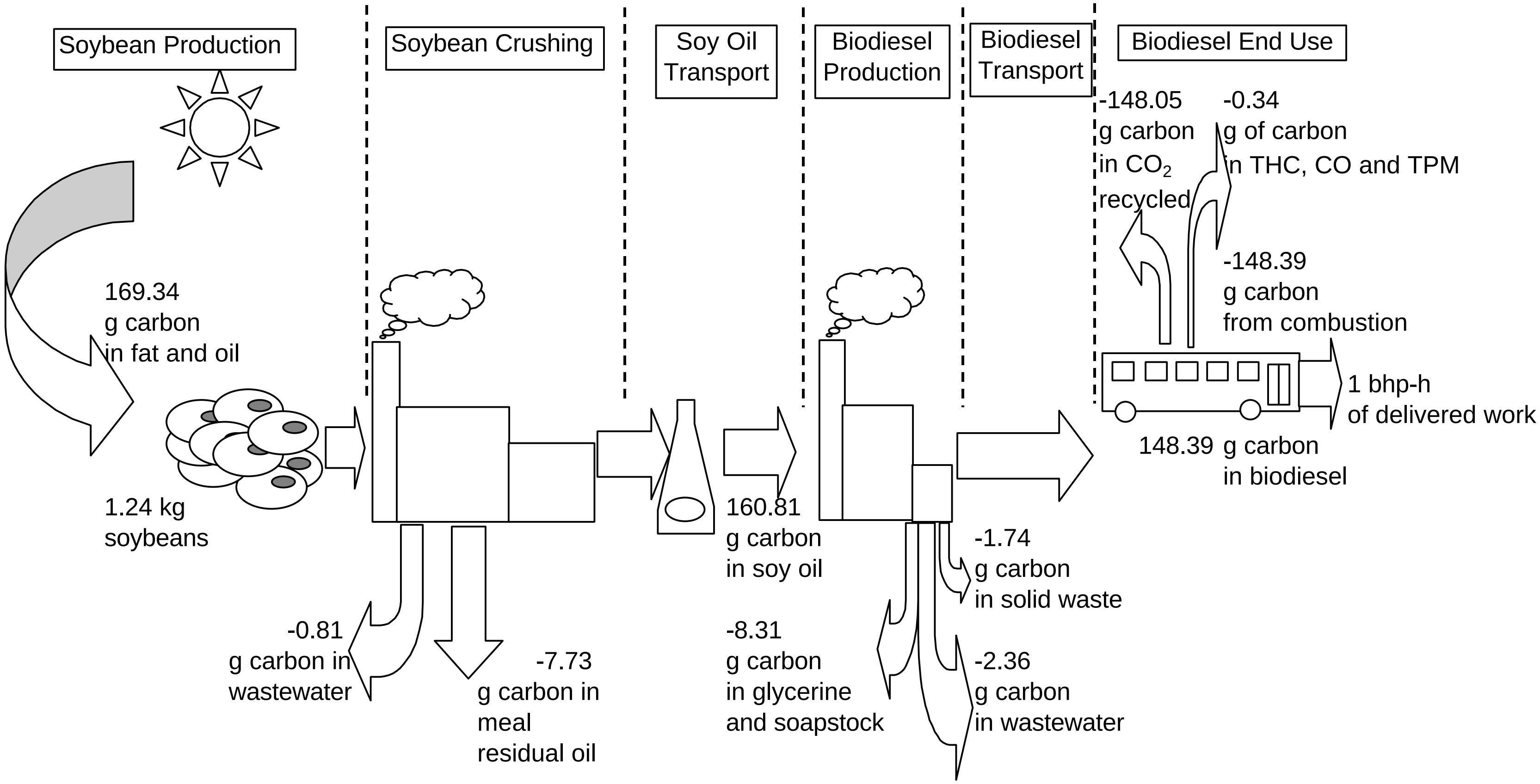


Figure 7: Biomass Carbon Balance for Biodiesel Life Cycle (g carbon/bhp-h)[11]

[11] All numbers presented as carbon equivalent. To calculate actual CO_2 emissions, multiply carbon equivalent numbers by 3.67 (the ratio of the molecular weight of CO_2 divided by the molecular weight of carbon).

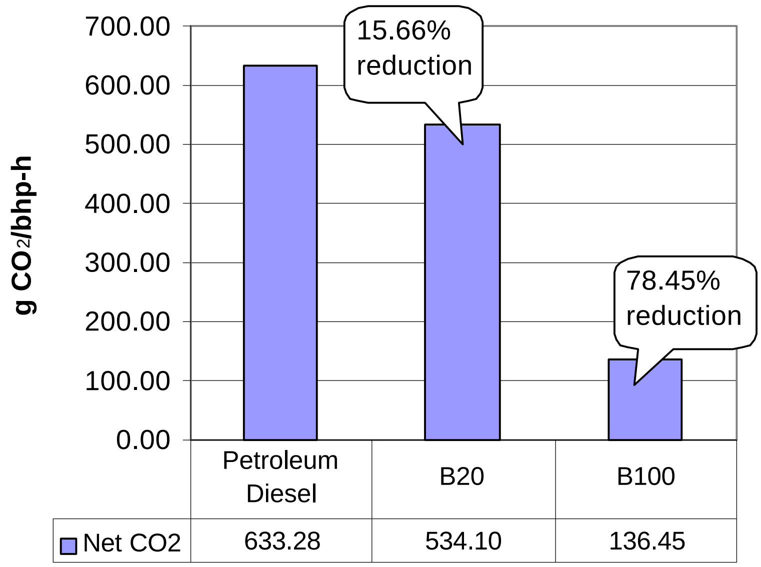


Figure 8: Comparison of Net CO_2 Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends[12]

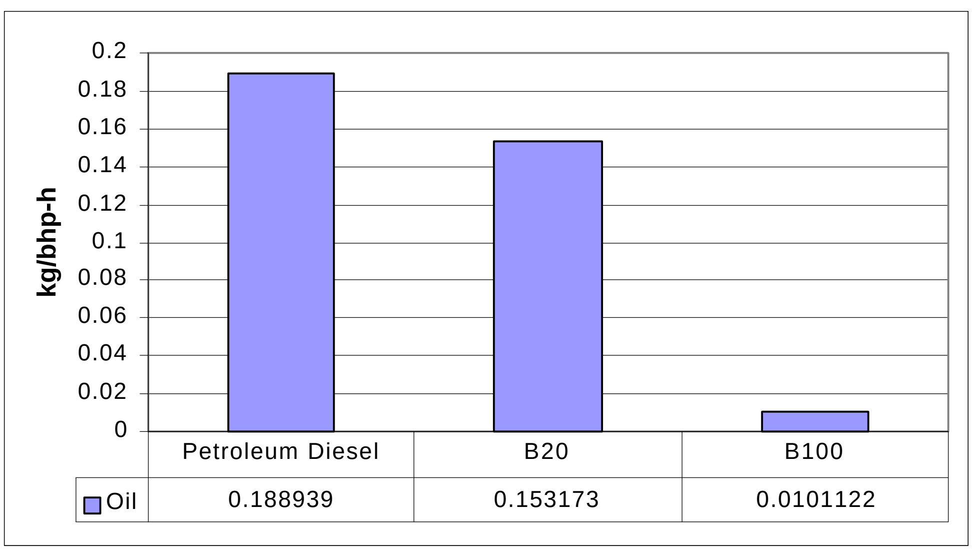
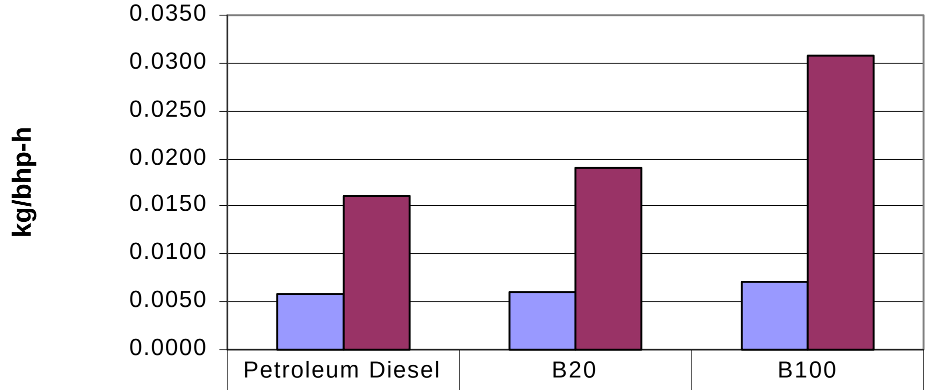


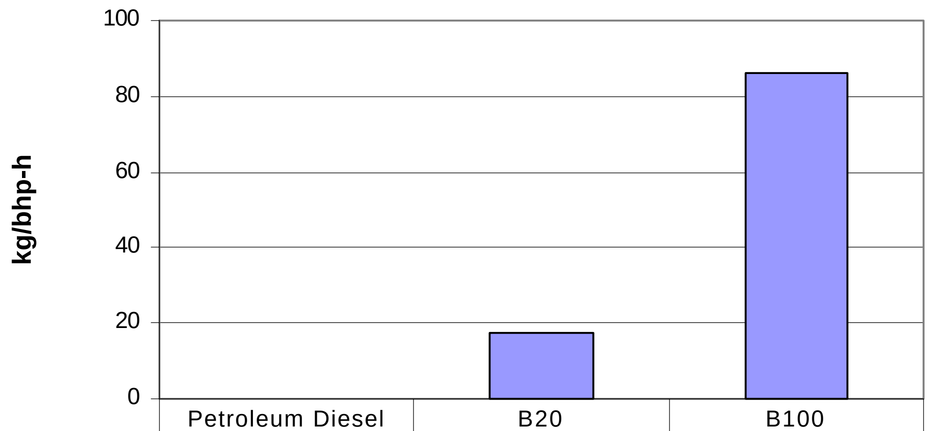
Figure 9: Petroleum Consumption for Petroleum Diesel, B20, and B100

[12] Net CO_2 calculated by setting biomass CO_2 emissions from the tailpipe to zero.



	Petroleum Diesel	B20	B100
Coal	0.0059	0.0061	0.0070
Natural Gas	0.0162	0.0191	0.0307

Figure 10: Coal and Natural Gas Consumption for Petroleum Diesel, B20, and B100



	Petroleum Diesel	B20	B100
Water	0.0262924	17.2938	86.3636

Figure 11: Water Use for Petroleum Diesel, B20, and B100

2.4.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants

Regulated air pollutants include the following:

- Carbon Monoxide (CO)
- Nitrogen Oxides (NO_x)
- Particulate Matter Less Than 10 Microns (PM10)
- Sulfur Oxides (SO_x)
- Non Methane Hydrocarbons (NMHC)

The emissions of these air pollutants are regulated at the tailpipe for diesel engines. Sulfur dioxide (SO_x) does not have specific tailpipe limits, but it is controlled through sulfur content of the fuel. Other air emissions included in this study are methane (CH_4), benzene, formaldehyde, nitrous oxide (N_2O), hydrochloric acid (HCl), hydrofluoric acid (HF), and ammonia. N_2O is associated with agricultural field emissions. HCl and HF are associated with coal combustion in electric power stations. Ammonia is released primarily during fertilizer production.

2.4.1.4.1 Comparison of Life Cycle Air Emissions for Biodiesel and Petroleum Diesel

Figure 12 summarizes the differences in life cycle air emissions for B100 and B20 versus petroleum diesel fuel. In this section, we discuss overall differences in the emissions of the biodiesel and petroleum life cycles. More detail on the sources of the differences is presented in section 9.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants.

We report particulate matter and hydrocarbons differently from the definitions used by EPA in their regulations. This difference in reporting is due to variations in how different data sources for the stages of the life cycle report these emissions. Benzene and formaldehyde emissions are not consistently reported. Some sources explicitly define emissions for non-methane hydrocarbons (NMHC), while others do not specify this distinction. Hydrocarbon data are reported as THC, defined as:

$$THC = \left(CH_4 + Benzene + formaldehyde + HC_{unspecified} + HC_{noCH4}\right)$$

where:

THC = total hydrocarbons

CH_4 = methane

$HC_{unspecified}$ = unspecified hydrocarbons

HC_{noCH4} = hydrocarbons excluding methane

Likewise, particulates are combined as a single category according to the following formula:

$$TPM = \left(PM10 + PM_{unspecified}\right)$$

where:

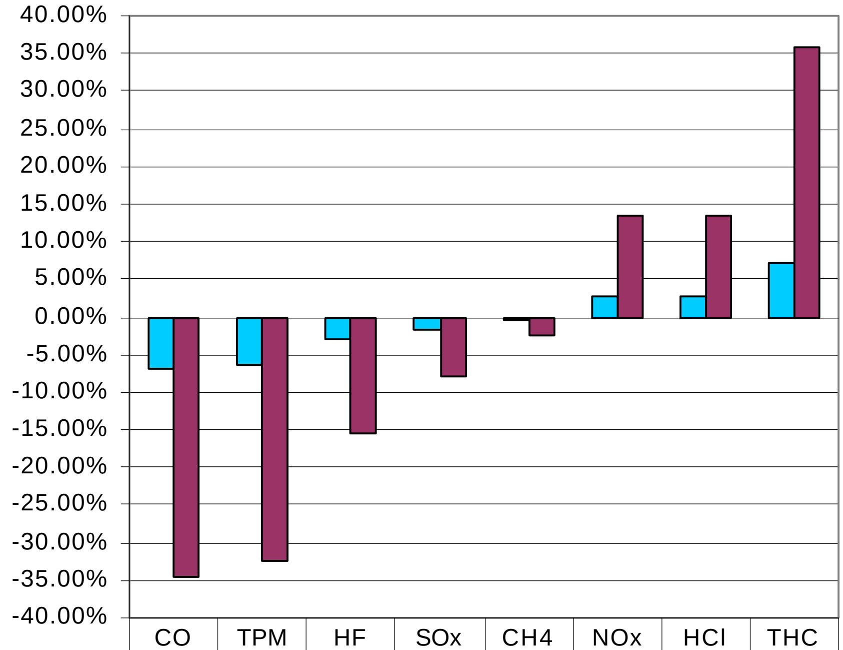
TPM = total particulate matter

PM10 = particulate matter less than 10 micron

$PM_{unspecified}$ = unspecified particulate matter

The replacement of petroleum diesel with biodiesel in an urban bus reduces life cycle air emissions for all but three of the pollutants we tracked. The largest reduction in air emissions that occurs when B100 or B20 are used as a substitute for petroleum diesel is for CO. Reductions in CO reach 34.5% when using B100. The effectiveness of B20 in reducing life cycle emissions of CO drops proportionately with the blend level. Biodiesel could, therefore, be an effective tool for mitigating CO in EPA's designated CO non-attainment areas[13].

[13] These are urban areas in the U.S. identified as not currently meeting National Ambient Air Quality Standards for levels of carbon monoxide.



	CO	TPM	HF	SOx	CH4	NOx	HCl	THC
B20	-6.90%	-6.48%	-3.10%	-1.61%	-0.51%	2.67%	2.71%	7.19%
B100	-34.50	-32.41	-15.51	-8.03%	-2.57%	13.35%	13.54%	35.96%

Figure 12: Life Cycle Air Emissions for B100 and B20 Compared to Petroleum Diesel Life Cycle Air Emissions

B100 exhibits life cycle emissions of total particulates (TPM) that are 32.41% lower than those of the petroleum diesel life cycle. As with CO, the effectiveness of biodiesel in reducing TPM drops proportionately with blend level. This improvement in TPM emissions is a direct result of reductions in PM10 at the tailpipe of the bus. Tailpipe emissions of PM10 are 68% lower for urban buses operating on B100 versus petroleum diesel. PM10 emitted from mobile sources is a major EPA target because of its role in respiratory disease. Urban areas represent the greatest risk in terms of numbers of people exposed and level of PM10 present. Use of biodiesel in urban buses is potentially a viable option for controlling both life cycle emissions of TPM and tailpipe emissions of PM10[14].

Biodiesel's life cycle produces 35% more THC than petroleum diesel's life cycle. This is in spite of the fact that tailpipe emissions of THC for B100 are 37% lower. The level of emissions of hexane that occur in the soybean crushing stage overshadows the tailpipe benefits[15]. In understanding the implications of the higher life cycle emissions, it is important to remember that emissions of hydrocarbons, as with all of the air pollutants discussed, have localized effects. In other words, it makes a difference *where* these emissions occur. The fact that biodiesel's hydrocarbon emissions at the tailpipe are lower may mean that

[14] Among the options under consideration by EPA are regulations that would control levels of PM2.5, as opposed to PM10. PM2.5 includes particles of 2.5 microns or less in diameter. That is, EPA is focusing its attention on the very smallest particles in ambient air. Data collected in this study focus on PM10. While our results bode well for lowering levels of PM10, no information is available on the effect of biodiesel on this new class of smaller particles.

[15] See section 9.1.4.3 Comparison of Life Cycle Air Emissions from Biodiesel and Petroleum Diesel for more details.

the biodiesel life cycle has beneficial effects on urban area pollution. We offer no judgement in this report regarding the impacts of these emissions because that discussion is beyond the scope of this report.

CH_4 emissions are 25% and 32% of the life cycle emissions of THC for B100 and B20, respectively. All these CH_4 emissions occur in the fuel production and utilization steps. Life cycle emissions of CH_4 are 2.57% and 0.51% lower for B100 and B20, respectively, compared to petroleum diesel. Though the reductions achieved with biodiesel are small, they could be significant when estimated on the basis of its "CO_2 equivalent"-warming potential.[16]

Perhaps the next most critical pollutant from the perspective of human health and environmental quality is NO_x. The triumvirate of CO, THC, and NO_x is the key to controlling ground-level ozone and smog in urban areas. The relative importance of each of these precursors is not at all clear because they interact in a complex set of chemical reactions catalyzed by sunlight[17]. Biodiesel effectively reduces tailpipe emissions of two of the three smog precursors (CO and THC). However, both B100 and B20 have life cycle *and* tailpipe emissions of NO_x that are higher than those of petroleum diesel. B100 and B20 exhibit 13.35% and 2.67% higher life cycle emissions, respectively, compared to petroleum diesel. It is almost an aphorism in the engine industry that TPM and NO_x emissions are two sides of a technology trade-off. Biodiesel seems to fit this observation. Dealing with this trade-off involves a combination of fuel research and engine technology research. Within these two arenas, solutions are potentially achievable that meet the tougher future standards for NO_x without sacrificing the other benefits of this fuel.

B100 and B20 life cycle emissions of SO_x are lower than those of petroleum diesel (8.03% and 1.61%, respectively). This is a relatively low reduction given that biodiesel completely eliminates SO_x at the tailpipe. The amount of SO_x in the emissions from a diesel engine is a function of sulfur content in the fuel. With this in mind, EPA regulates diesel fuel's sulfur content, rather than tailpipe SO_x emissions. The latest requirements for diesel fuel include 0.05 wt% sulfur for on-highway fuel. Biodiesel can eliminate SO_x emissions because it is sulfur-free. The complete elimination of SO_x at the tailpipe is offset by emissions of SO_x associated with the higher demand for electricity in the biodiesel life cycle versus the petroleum diesel life cycle[18]

HCl and HF emissions are emitted in very low levels as a part of the life cycles of both petroleum diesel and biodiesel. They are tracked in this study because of their potential contribution to acidification effects in the environment. Both pollutants occur as a result of coal combustion in electric power generation. HF levels drop with biodiesel in proportion to the amount of electricity consumed over the life cycle of the fuel. This amounts to 15.51% reductions for B100. HCl emissions, on the other hand, increase with biodiesel blend. Biodiesel has additional sources of HCl associated with the production and use of inorganic acids and bases used in the conversion step. B100 increases emissions of HCl by 13.54%.

2.4.1.5 Life Cycle Emissions of Water Effluents

We tracked a number of waterborne effluents through the life cycles for petroleum diesel and biodiesel such as BOD (biological oxygen demand) and COD (chemical oxygen demand). However, relatively few data were consistently available. Therefore, the comparisons of the two life cycles are limited to total

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[16] Although CH_4 is a more potent greenhouse gas, its half-life in the atmosphere is less than that of CO_2. These complications in understanding the impact of each pollutant illustrate why we have avoided making quantitative judgements about the life cycle impacts of biodiesel. We leave it to others to evaluate the comparative inventories of biodiesel and diesel in terms of their positive and negative impacts.

[17] For an excellent discussion of the complexities of urban air pollution, see Seinfeld, John H., "Urban Air Pollution: State of the Science" in *Science, Vol 243*, pp 745-752.

[18] See section 9.1.4.3 for a more thorough discussion of sources of SO_x in the two fuel life cycles.

flow of wastewater. Foreign and domestic crude oil extraction account for 78% of the total wastewater flow in the petroleum diesel life cycle. Only about 12% is associated with the refinery. Two-thirds of the total wastewater flows in the life cycle for biodiesel come from the soy oil conversion process. This step in the life cycle generates relatively dilute wastewater containing oil and soap from the processing of the soybean oil. A comparison of total wastewater flows from the life cycles for petroleum diesel and biodiesel is shown in Figure 13. Petroleum diesel generates roughly five times as much wastewater flow as biodiesel.

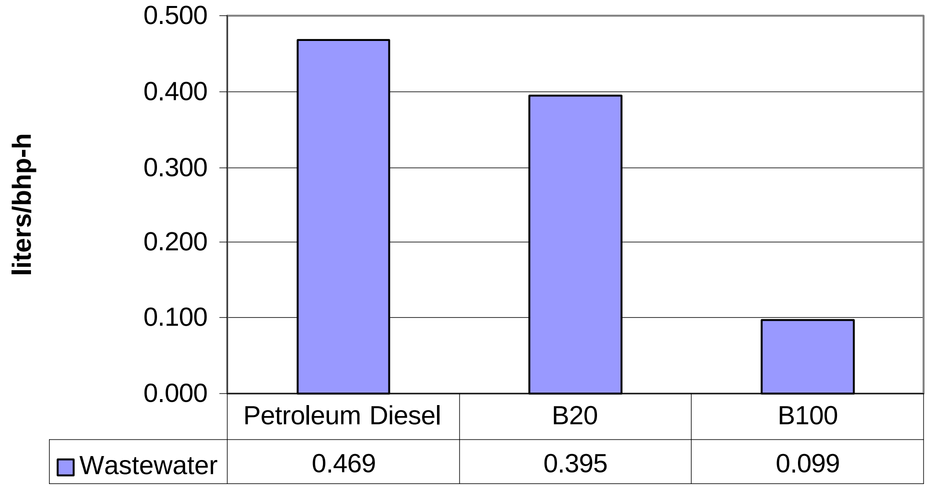


Figure 13: Comparison of Total Wastewater Flows for Petroleum Diesel and Biodiesel Life Cycles

2.4.1.6 Comparison of Solid Waste Life Cycle Flows

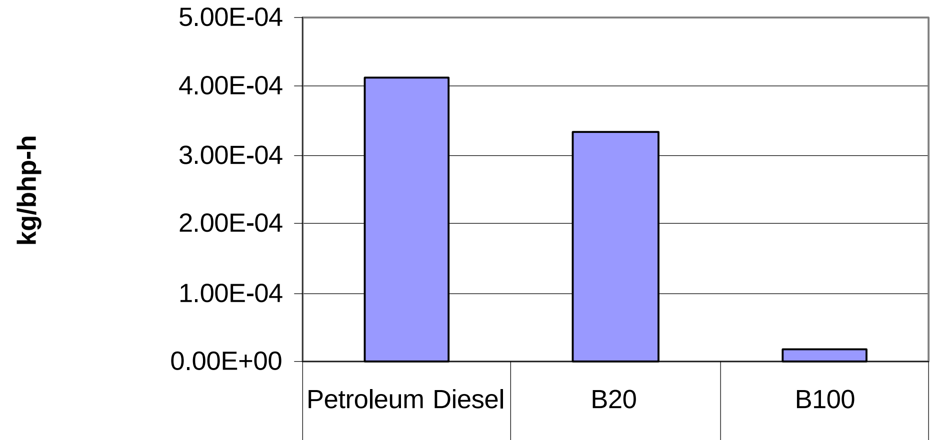
Solid waste from the two life cycles is classified as hazardous or nonhazardous. In the petroleum diesel life cycle, hazardous waste is derived almost entirely from the crude oil refining process. The minor levels of solid waste that show up in foreign crude transport and diesel fuel transport are indirect flows of solid waste attributable to production of diesel fuel and gasoline used in the transportation process. Total hazardous waste generation amounts to 0.41 g/bhp-h of engine work. About half the nonhazardous waste is generated by petroleum diesel is in the crude oil refining step. Another one-third is generated in the foreign and domestic crude oil extraction steps. Total nonhazardous waste generation in the petroleum diesel life cycle is 2.8 g/bhp-h.

Hazardous waste from the biodiesel life cycle amounts to only 0.018 g/bhp-h of engine work. Soybean agriculture contributes 70% of the hazardous waste from the entire life cycle, but these flows are indirect charges against agriculture for hazardous waste flows associated with the production of diesel fuel and gasoline used on the farm. Nonhazardous solid waste generated in the biodiesel life cycle 12.7 g/bhp-h of engine work. This waste is primarily trash and tramp metals removed from soybeans brought into the soybean crushing stage. Figure 14 and Figure 15 show hazardous and nonhazardous solid waste generation for petroleum diesel and biodiesel. The B100 life cycle produces 96% less hazardous waste compared to petroleum diesel life cycle. Nonhazardous waste, on the other hand, is twice as high for B100.

2.4.2 Sensitivity Studies

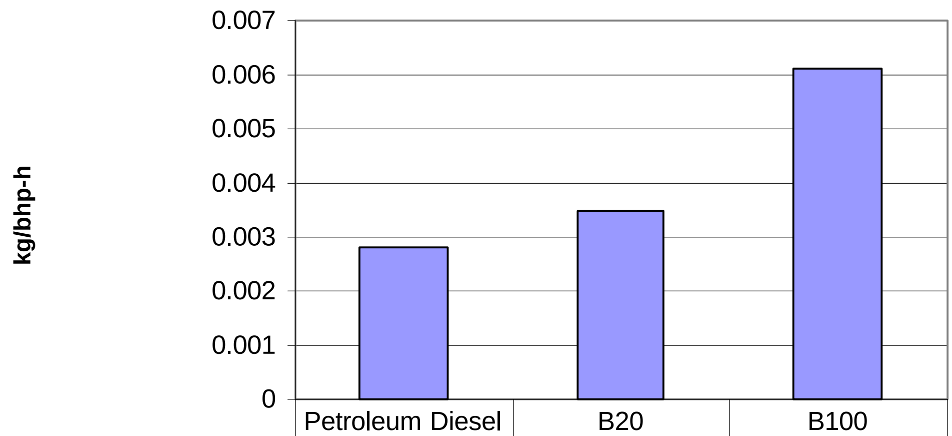
2.4.2.1 The Effect of Enhanced Location for Biodiesel Production and Use

We studied the effect of placing biodiesel production and use in a more optimal location, which mimics how similar renewable fuels industries, such as ethanol, have developed. To that end, we chose to model biodiesel production and use in the Chicago area. This location provides a good outlet for biodiesel sales for the urban bus end-use. More importantly, it allows us to consider near-term access to some of the best soybean farmland in the United States. This scenario reduces the distances required to move beans, oil, and biodiesel, and allows us to take advantage of high-yield soybean agriculture.



	Petroleum Diesel	B20	B100
Hazardous Waste	4.13E-04	3.34E-04	1.82E-05

Figure 14: Hazardous Waste Generation for Petroleum Diesel, B20, and B100



	Petroleum Diesel	B20	B100
Nonhazardous Waste	0.00282423	0.00348482	0.00612718

Figure 15: Nonhazardous Waste Generation for Petroleum Diesel, B20, and B100

Basic changes to the model are shown in Table 8. The reduced distance for shipping soybean oil is based on an evaluation of the location of crushing facilities to potential market locations. The results of the model with these assumptions is presented for B100, with the understanding that the improvements or worsening in life cycle emissions relative to petroleum diesel are proportional to the blend level.

Table 8: Model Parameters for the Chicago Area Biodiesel Scenario

Model Parameter	Baseline Scenario	Chicago Area Scenario
Soybean Agriculture	Yields and inputs based on national average (14 key soybean-producing states)	Yields and inputs based on production of soybeans from Illinois and Iowa. 50% of soybean supply is taken from each state.
Transport Distances	National average distance for soy oil of 571 miles	Reduced travel distance of 248 miles.

Placing biodiesel production and use in the Chicago area has benefits for energy consumption (see Figure 16). Impacts on natural gas and coal consumption are minor (2% and 5% savings, respectively). Petroleum consumption, on the other hand, drops by 23.53% from the national average base case. This leads to a slight increase in life cycle energy efficiency from the base case value of 80.55% to 81.84%. Biodiesel's fossil energy ratio increases from 3.22 to 3.43. The energy savings occur primarily on the farm. Process energy requirements for farming drop by 22%. Energy savings of 56% are also realized in the soy oil transport step, but this impact is smaller because of the relatively small contribution to energy demand made by this step. Water use drops dramatically in the Chicago area scenario. Biodiesel consumes 31% less water in this scenario.

The percent reductions of key air pollutants are tabulated in Figure 17. The change to a more favorable location has, with one exception, modest benefits for air emissions. The exception is for ammonia emissions, which drop by 45%. Ammonia emissions occur as a result of nitrogen fertilizer use. The large drop in life cycle ammonia emissions is due to improved yields and lower nitrogen fertilizer usage rates per kg of soybeans produced. The next largest saving is for PM10 emissions, which drop 10% from the base case. This is consistent with the reductions in petroleum consumption associated with diesel fuel use on the farm. The Chicago scenario provides an additional savings of 7% in CO_2 emissions. All other emissions savings are less than 5%, compared to the base case.

Reductions in life cycle waste emissions are shown in Figure 18. Hazardous waste emissions are reduced dramatically. The 28% reduction corresponds to lower levels of diesel fuel use in the farming of soybeans. Wastewater and nonhazardous solid waste reductions are 5.79% and 2.72%, respectively.

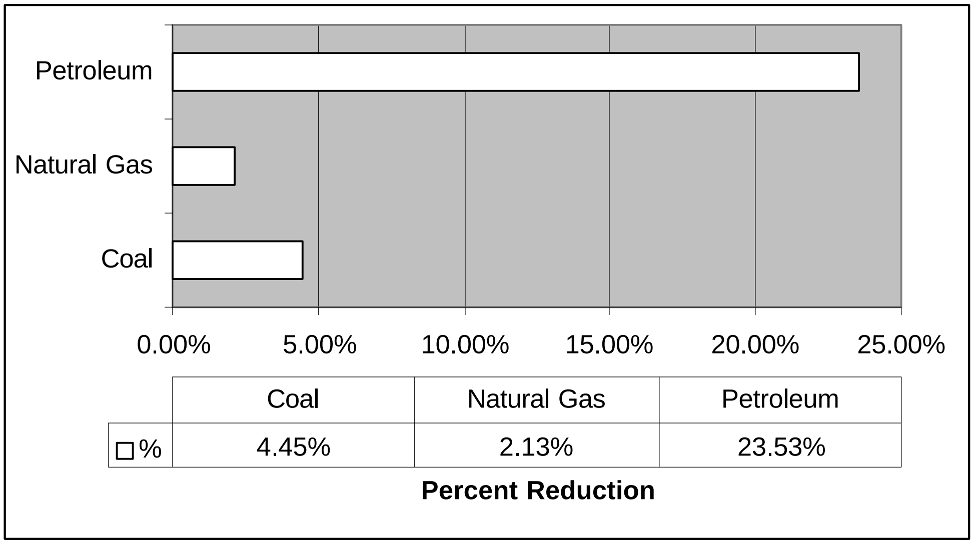


Figure 16: The Effect of an Enhanced Location for Biodiesel on Life Cycle Consumption of Primary Energy Resources

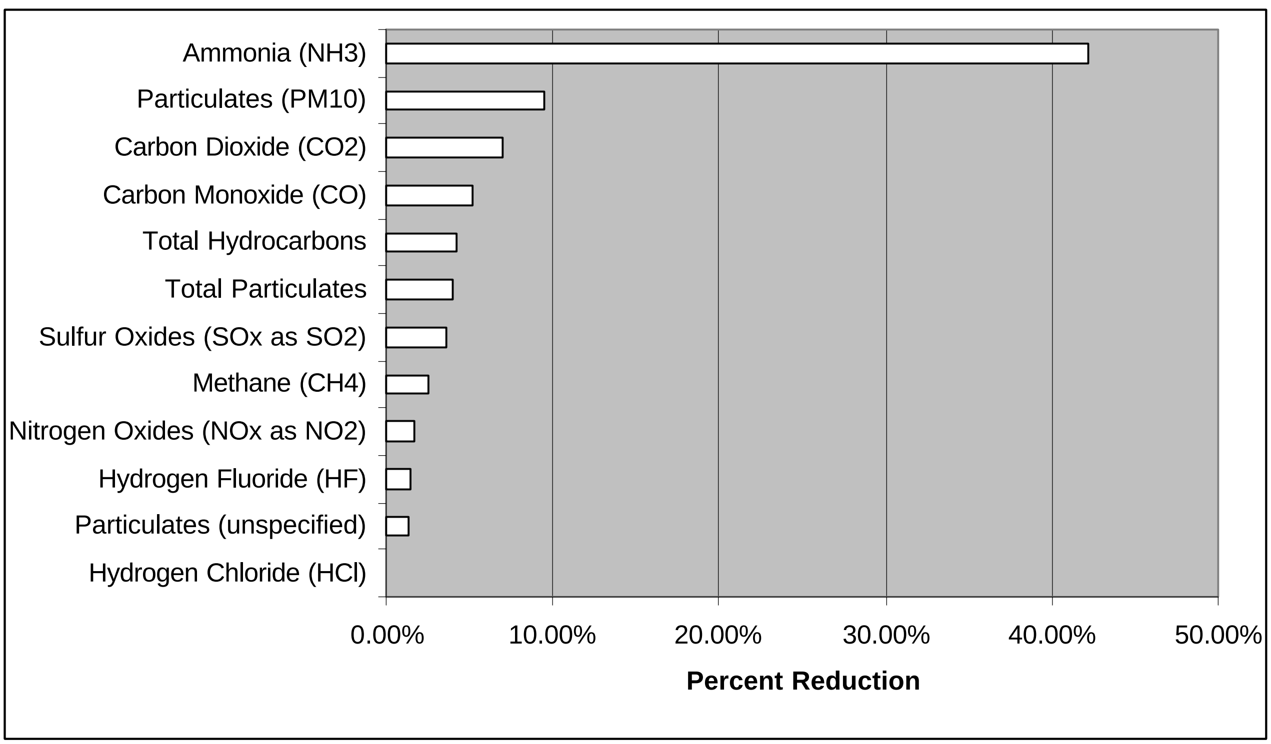


Figure 17 : Reductions in Life Cycle Air Emissions for the Chicago Area Biodiesel Scenario

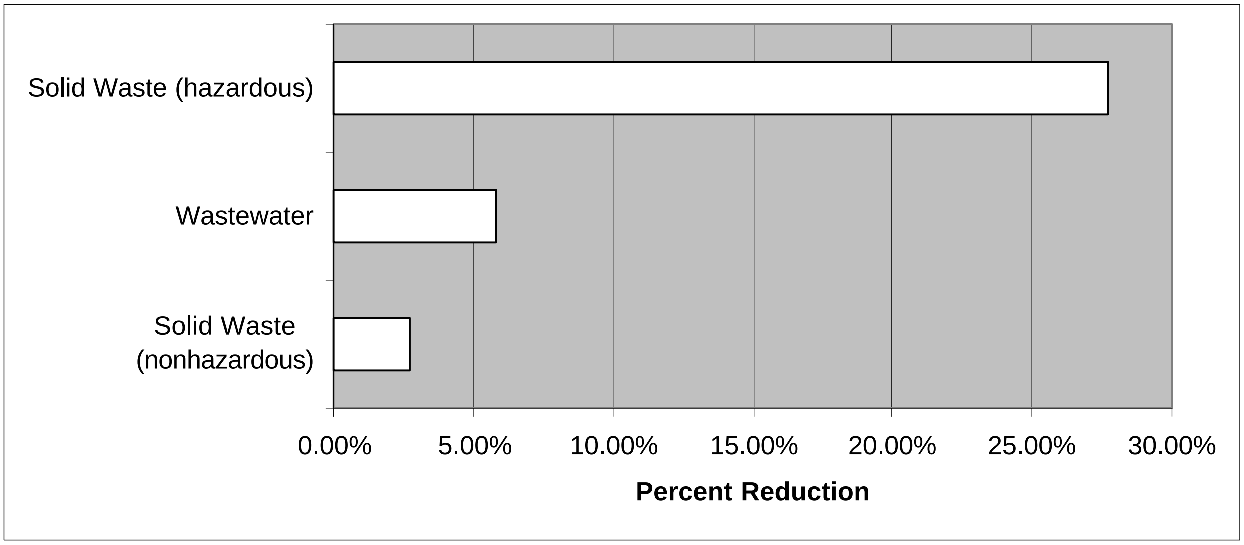


Figure 18: Water and Solid Waste Emissions Reductions for the Chicago Area Biodiesel Scenario

2.4.2.2 The Effect of Energy Requirements for Conversion of Soybean Oil to Biodiesel

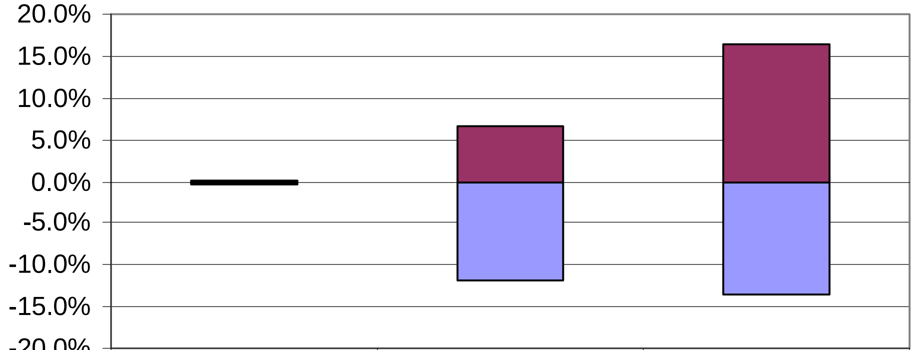
A range of energy inputs for converting soybean oil to biodiesel was used in the LCI model to test the effect of these modeling assumptions on the overall LCI of biodiesel. A survey of current commercial technology for biodiesel reveals a high degree of variation on reported steam and electricity requirements for the transesterification process. High and low estimates for both steam and electricity used in the model are indicated in Table 9.

Table 9: Range of Energy Inputs for Soybean Oil Conversion Tested in LCI Model

Energy Use	Low Value	Baseline Scenario	High Value
Steam (kcal/metric ton of biodiesel produced)	95,022.7	329,793.5	617,922.2
Electricity (kWh/metric ton of biodiesel produced	9.0	28.9	40.0

Steam requirements vary 3.5-fold from the lowest to the highest value. Electricity varies 4.4-fold. This high degree of variability warrants testing the range of these assumptions in our model in order to assess the uncertainty of our overall results related to this assumption. Furthermore, energy inputs for soybean oil conversion are a substantial part of the life cycle, making this variability even more important.

The effect of conversion energy variability on the demand for primary energy resources is shown in Figure 19. Overall effects on primary energy are considerably smaller than the range of variation in energy inputs. Oil consumption is not affected at all. Because natural gas is the sole source of process energy in the conversion model, it is the most affected by the energy requirements assumed for this stage. Natural gas consumption increases 16.41% for the high energy inputs and decreases by 13.5% for the low energy inputs. Coal consumption ranges from +6.55% to –11.7% of the base case.

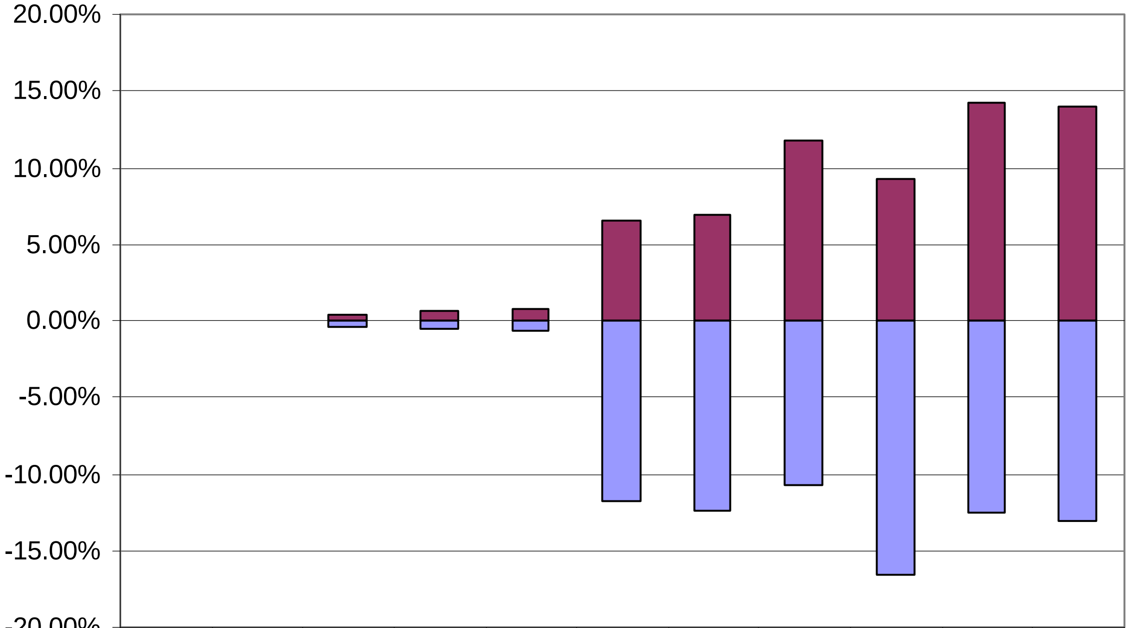


	Oil	Coal	Natural Gas
% High	0.16%	6.55%	16.41%
% Low	-0.3%	-11.7%	-13.5%

Figure 19: The Effect of Conversion Energy Requirements on Primary Energy Resource Demands for Biodiesel

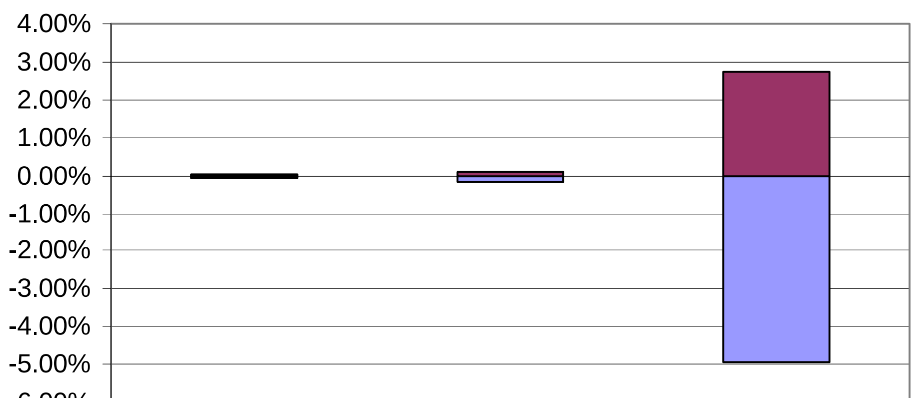
Figure 20 presents changes in biodiesel's life cycle air emissions across the range of assumed energy requirements for conversion of soybean oil. Life cycle emissions are listed in order of increasing sensitivity to energy requirement assumptions. Changes in steam requirements (and hence natural gas consumption) have a large effect on CH_4 emissions, which can vary by 14% in both directions. From a greenhouse gas perspective, this is probably the most significant change observed in this sensitivity study. CO_2 shows similar responses. Unspecified PM and SO_x emissions are also affected significantly, reflecting emissions from combustion for electricity generation. No other emissions show much response to the energy inputs for soy oil conversion.

The relative changes in solid waste and wastewater emissions are presented in Figure 21. Wastewater and hazardous solid waste emissions hardly change at all across the range of assumed energy requirements. Nonhazardous solid waste does show a moderate response.



	HC unspec	HC less CH4	NOx	CO	PM10	PM unspec	HCl	CO2	HF	SOx	CH4
% High	0.03%	0.04%	0.43%	0.63%	0.76%	6.60%	6.91%	11.83%	9.29%	14.25%	14.03%
% Low	-0.04%	-0.04%	-0.43%	-0.55%	-0.62%	-11.82%	-12.39%	-10.66%	-16.65%	-12.54%	-13.13%

Figure 20: The Effect of Soybean Oil Conversion Energy Demands on Air Emissions for Biodiesel



	Wastewater	Solid Waste (Hazardous)	Solid Waste (Non-hazardous)
% High	0.04%	0.11%	2.75%
% Low	-0.06%	-0.19%	-4.93%

Figure 21: The Effect of Soybean Oil Conversion Energy Demands on Water and Solid Waste Emissions for Biodiesel

2.5 Conclusions

Conducting LCIs is fraught with difficulties. Incomplete data are the rule rather than the exception. We have varying degrees of confidence in the results we present in this report. The most reliable conclusions of this study are for overall energy balance and CO_2 emissions. For these two measures, our data are the most complete. More importantly, our sensitivity studies show that the estimates of CO_2 emissions and energy requirements are very robust; that is, these results show little change in response to changes in key assumptions.

2.5.1 Life Cycle Energy and Environmental Flows

Major analytical results are presented below in order of decreasing confidence:

- ***Energy Balance***. Biodiesel and petroleum diesel have very similar energy efficiencies. The base case model estimates life cycle energy efficiencies of 80.55% for biodiesel versus 83.28% for petroleum diesel. The lower efficiency for biodiesel reflects slightly higher process energy requirements for converting the energy contained in soybean oil to fuel. In terms of effective use of fossil energy resources, biodiesel yields around 3.2 units of fuel product energy for every unit of fossil energy consumed in the life cycle. By contrast, petroleum diesel's life cycle yields only 0.83 units of fuel product energy per unit of fossil energy consumed. Such measures confirm the "renewable" nature of biodiesel. The life cycle for B20 has a proportionately lower fossil energy ratio (0.98 units of fuel product energy for every unit of fossil energy consumed). B20's fossil energy ratio reflects the impact of adding petroleum diesel into the blend.

- ***CO_2 Emissions***. Given the low demand for fossil energy associated with biodiesel, it is not surprising that biodiesel's life cycle emissions of CO_2 are substantially lower. Per unit of work delivered by a bus engine, B100 reduces net emissions of by 78.45% compared to petroleum diesel. B20's life cycle CO_2 emissions of CO_2 are 15.66% lower than those of petroleum diesel. Thus, use of biodiesel to displace petroleum diesel in urban buses is an extremely effective strategy for reducing CO_2 emissions.

- ***Total Particulate Matter (TPM) and Carbon Monoxide (CO) Emissions***. The biodiesel (B100) life cycle produces less TPM and CO (32% and 35% reductions, respectively) than the petroleum diesel life cycle. Most of these reductions occur because of lower emissions at the tailpipe. PM10 emissions from an urban bus operating on biodiesel are 63% lower than the emissions from an urban bus operating on petroleum diesel. Biodiesel reduces tailpipe emissions of CO by 46%.

- ***NO_x Emissions***. At the same time, NO_x emissions are 13% higher for the B100 life cycle compared to the petroleum diesel life cycle. B20 has 2.67% higher life cycle emissions of NO_x. Again, this increase is attributed to higher NO_x emissions that occur at the tailpipe. An urban bus run on B100 has NO_x emissions that are 8.89% higher than a bus operated on petroleum diesel.

- ***Total Hydrocarbons (THC)***. We also report 35% higher life cycle emissions of THC compared to petroleum diesel. Tailpipe emissions of THC are actually 37% lower for B100, compared to petroleum diesel. The increase in hydrocarbon emissions is due to release of hexane during soybean processing and to volatilization of agrochemicals applied on the farm. We have less confidence in the hydrocarbon air emissions results from this study. Air emissions data are often not reported on the same basis. For example, data run the gamut from specific hydrocarbon compounds such as CH_4 or benzene to broad measures of total hydrocarbons. The latter are not measured consistently, as well. Our data set includes numbers reported as "unspecified hydrocarbons" and as "non-methane hydrocarbons" (NMHC). Given these kinds of ambiguities in the data, results on hydrocarbon emissions need to be viewed with caution.

- ***Water and Solid Waste***. We report total wastewater and solid waste flows. Our results show that biodiesel has life cycle wastewater flows that are almost 80% lower than those of petroleum diesel. Hazardous waste generation is also much lower for biodiesel. Biodiesel generates only 5% of the amount of hazardous waste generated by petroleum diesel. However, we do not have a consistent basis for comparing these flows because their final disposition and composition are so different.
- ***Water consumption.*** B100 uses water at a level that is three orders of magnitude higher than petroleum diesel, on a life cycle basis.

2.5.2 Next Steps

At the outset, we designed this study to identify and quantify the advantages of biodiesel as a substitute for petroleum diesel. These advantages are substantial, especially in the area of energy security and control of greenhouse gases. We have also identified weaknesses or areas of concern for biodiesel—such as its emissions of NOx and THC. We see these as opportunities for further research to resolve these concerns. We hope that our findings will be used to focus future biodiesel research on these critical issues.

Much that could be done to build on and improve the work we have done here. Appropriate next steps for this work include the following:

- ✓ Use the LCI to assess the relative effects of petroleum diesel and biodiesel on our environment and on public health risks in order to gain an understanding of the benefits associated with biodiesel.
- ✓ Quantify the costs and benefits of biodiesel.
- ✓ Assess the economic impact of biodiesel as an alternative fuel (e.g., its effects on jobs, trade deficit, etc.).
- ✓ Evaluate other feedstock sources.
- ✓ Incorporate new health effects data on emissions from biodiesel and petroleum diesel.
- ✓ Develop regional life cycle models for biodiesel use.
- ✓ Evaluate performance of newer diesel engines and new fuel production technologies.

This study provides the building blocks for others to assess the relative merits of this fuel under a wide variety of circumstances, to which this country could be exposed. On a smaller scale, it provides the type of information that local regulators always seek when developing approaches to solving our air, water, and solid waste problems. We leave it to these individuals to use this information to customize their evaluations of their particular questions. We ask only that it be used wisely.